Laboratory Experiment of Air Residence Time in a Side Rectangular Cavity

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Abstract

Dispersion phenomena in underground mine ventilation system is an important parameter in controlling the spreading of gas or other particulate matter throughout the mine. From the results of tracer gas measurement in underground mine ventilation, it was found that the evaluated dispersion coefficient is larger than theoretical value. The presence of cavities and dead ends in along mine ventilation airways are supposed to be the main cause of this finding. The trapped gas inside cavity also harmful for workers, therefore adequate ventilation should be provided to dilute. In present study, the air residence time in a cavity was investigated by using tracer gas released in cavity and the decay time was measured required for the gas to completely escaped. The air exchange rates and the cavity's ventilation efficiency were investigated in correlation with cavity's aspect ratio and free stream velocity.

Keywords

Tracer Gas; Cavity; Air Exchange Rate; Cavity's Ventilation Efficiency

Introduction

The tracer gas was firstly used in the building ventilation systems in the 1950s and has been widely used for ventilation analysis only in buildings and underground mines (Stokes, Kennedy and Hardcastle 1987). The tracer gas ventilation measurement is an effective method to detect air flow routes, estimate air flow quantity, and other complex ventilation problems (Widodo, Sasaki, Gautama, Risono, 2008; Arpa, Widiatmojo, Widodo, Sasaki 2008; Thimons and Kissell, 1974).

Sulphur hexafluoride (SF_6) is widely accepted as a standard tracer for mine ventilation because it can be detected even in low concentrations, non-toxic, odorless, colorless, chemically and thermally stable, and rarely exist in the natural environment (Thimons and Kissell, 1974). The applications of tracer gases in underground mines include measurements of turbulent diffusion (Arpa, Widiatmojo. Widodo, Sasaki 2008), methane emission control (Mucho, Diamond, Garcia, Byars, Cario, 2000). Tracer gas can be useful tools for analyzing ventilation recirculation of return into intake airways, transit flow times through dead spaces, effectiveness of auxiliary fans, and estimation of volumetric flow rates (Thimons and Kissell, 1974), air leakage and and dust control evaluation (Timko and Thimons, 1983).

Researches related to the air change rate measurement are mainly concerned with the building ventilation (Afonso, Maldonado, and Skaaret, 1986; Laporthe, Virgone, and Castanet, 2001; Skaret and Mathisen, 1982; Breum 1988, Bonthoux, Dessagne, and Aubertin 2004; Li, Li, and Dou, 2003). Despite the gases used in the measurements are different, most of measurement methods are similar. Generally, a specific gas released in the ventilated room and the air exchange rate was estimated from the decay of the tracer gas concentration.

The measurement is intended to determine the dilution rate or exchange of air in a semi-enclosed cavity by observing the rate at which the tracer concentration is diminished with time (the decay rate) and to clear the effect of free stream velocity and cavity's aspect ratio.

The mechanism of recirculation flow inside cavity is driven by average free stream velocity, U_m (m/s), and the vortices formed inside are affected by cavity's geometry and shape. Consequently, the practical estimation of gas mixing mechanism in the cavity is difficult.

Experimental Setup

The experiments were conducted by utilizing an open

loop wind tunnel representing the scaled model of a mine tunnel. The single side rectangular cavity was constructed in the bottom of test section. Figure (1) shows the illustration of the experimental setup. The Carbon Dioxide (CO_2) was used as tracer gas. Beforehand, it was confirmed that the effect of background CO_2 concentration was negligible. The CO_2 was released with constant flow rate and stopped after the constant reading or steady gas concentration was achieved. To allow sufficient radial mixing of tracer gas in perpendicular direction of free stream direction, the releasing probe was positioned far enough at upstream position before cavity. To confirm the stability, the measurement was repeated one time for each combination of main flow velocity and aspect ratio. The sampling tube was positioned at middle (pos #1) and bottom-rear corner of cavity the (pos #2) as shown in Figure (2). Figure (3) shows the typical acquired concentration-time curve from the measurement presented in normalized value of concentration against peak concentration (steady state concentration). The model of a rectangular cavity was constructed in an L_wxHxW_T (LengthxHeightxWidth) of 2.3x0.4x0.4m wind tunnel. The cavity has constant DxW(Depth x Width) of 0.12x0.4 m and the L/D ratios were varied by changing the cavity's length, L.

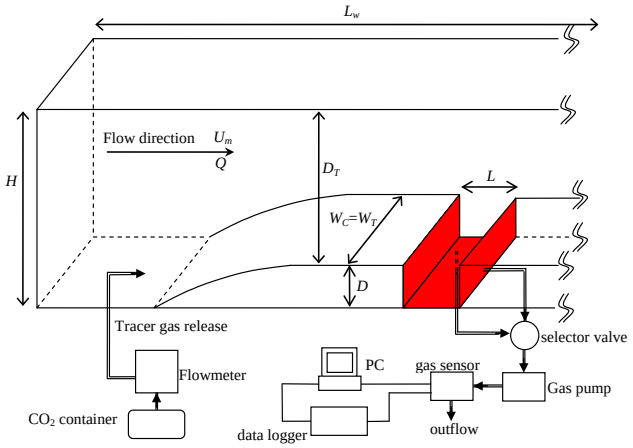

FIG. 1 SCHEMATIC FIGURE SHOWING EXPERIMENTAL SETUP TO MEASURE GAS CONCENTRATION DECAY TIME IN A CAVITY (RED COLORED).

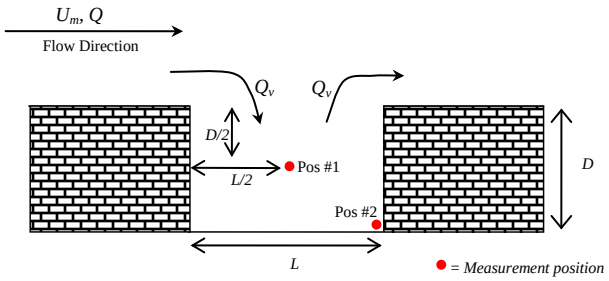

FIG. 2 SCHEMATIC FIGURE OF CROSS SECTIONAL CAVITY VIEW DESCRIBING SAMPLING LOCATION.

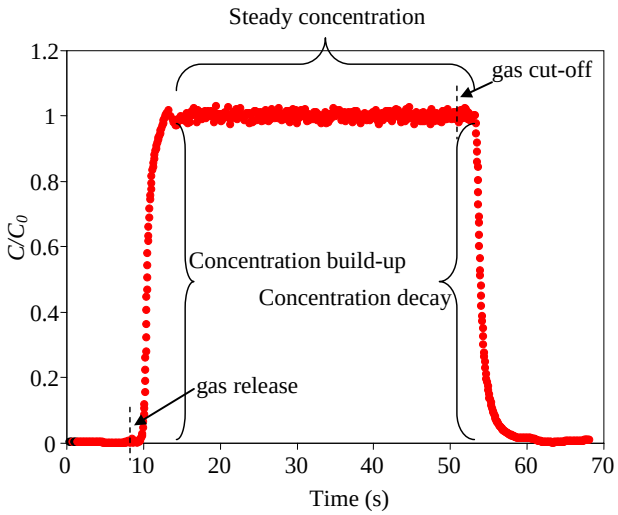

FIG. 3 TYPICAL MEASUREMENT RESULT SHOWS CONCENTRATION DECAY IN A RECTANGULAR CAVITY

Because airway in underground mine has to be scaled in the wind tunnel, the similarity criteria of Reynolds number must be fulfilled to get similar flow field condition compared to full scale airway. In present study, the Reynolds number was varied by changing free stream velocity as U_m=7.07 m/s, U_m=15.8m/s and U_m=20.4m/s (correspond to Re=1.46E+05, Re = 3.26E+05 and Re = 4.2E+05 respectively) and by considering hydraulic diameter of tunnel, d_h=2 r_h=0.165 m. On the other hand, Reynolds numbers for mine airways are varied depends on the average diameter and mean velocity. Underground airway for general purpose (main haulage routes, conveyor drift, ventilation shafts etc.) have Reynolds number varied from Re=5E+04 to Re=8E+05 (McPherson, 1993). Thus, the criterion is satisfied by present experimental set up. Effects of different aspect ratio, L/D, were evaluated by setting L/D= 0.5, 1 and 1.5 and constant span wise ratio, W_C/D=3.3.

Gas Analyzer Device

The DX6100 Gas Analyzer manufactured by RMT. Ltd, is specially designed for fast response, high sensitivity, low noise and low power consumption (see Figure 4). A number of design features contributing to the performance are:

- The sampling gas is continuous and the output data is able to record short sampling interval (0.1 s).
- The infrared sources are special narrow-band pulsed light emitters which operate in microsecond range. The light sources have long life (more then 10,000 hours).
- Radiation from Light Emitters passes through gas sampling cell reflecte from mirrors and is

focused on wide-band photo-detector.

- Both light emitters and photo-detector chips are integrated into a single housing and placed onto a miniature Thermo Electric (TE) cooler for thermo-stabilization.
- Microcontroller provides temperature regulation with better than 0.1°C accuracy. The temperature is software selectable from ambient down to –20°C.
- The dissipated heat from warm side of TE coolers, leads to few degrees of overheating of gas sampling cell above ambient. This factor plays the role of vapor anti-condensation at operation in wet conditions.
- All driving functions of Light Emitters and Detector are operated by on-board microcontroller.
- Pre-amplified outputs are maintained by the microcontroller. The final result is the digital data of measured gas concentration and is available in real-time through RS-232C or analog port.
- For signal processing, the calibrating data of Optical Unit is used. The data is stored in Optical Unit's EEPROM. The RS-232C port is also used for remote control from computer.

FIG. 4 THE (RMT. LTD, DX6100) CO_2 GAS ANALYZER USED IN THE EXPERIMENT

Measurement Results

Figures (5) to (7) show the decay of concentration at different *L/D* ratio and Reynolds number for measurement position #1, whereas Figure (8) to (10) show the result at measurement position #2. The effect of different aspect ratio as seen in all results shows faster decay of CO_2 concentration as the aspect ratio increases. From these results, in general, the gas escapes faster as the length of cavity increase. This is due to increasing lid area which allows more free stream air enter the cavity.

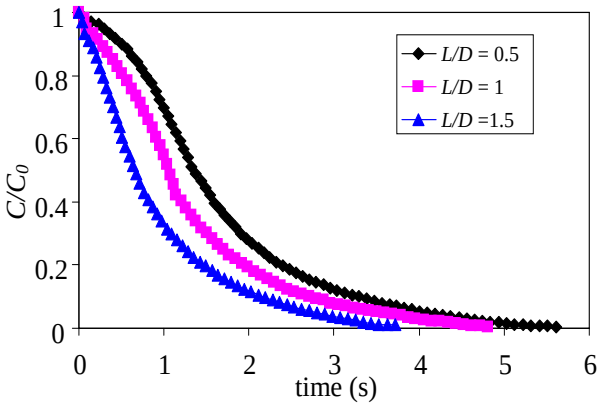

FIG. 5 CONCENTRATION DECAY FOR MEASUREMENT AT POS #1 AND U_m=7.07m/s.

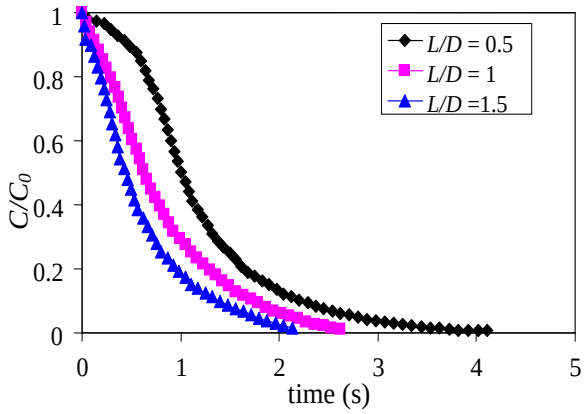

FIG. 6 CONCENTRATION DECAY FOR MEASUREMENT AT POS #1 AND U_m = 15.8m/s

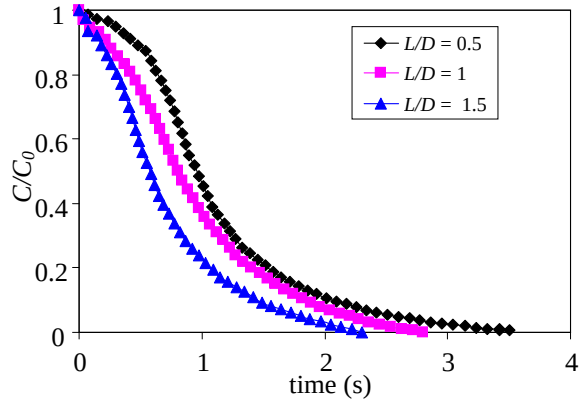

FIG. 7 CONCENTRATION DECAY FOR MEASUREMENT AT POS #1 AND U_m = 20.4m/s.

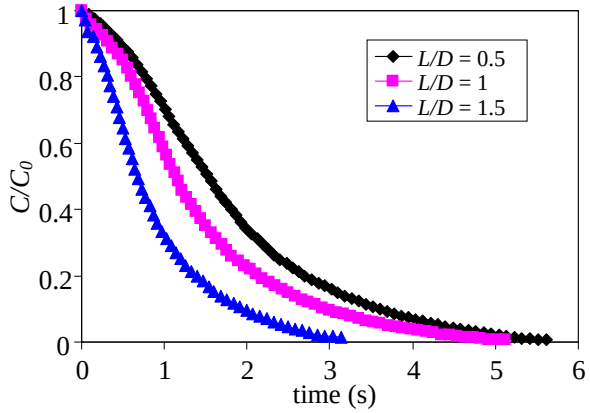

FIG. 8 CONCENTRATION DECAY FOR MEASUREMENT AT POS #2 AND U_m=7.07m/s

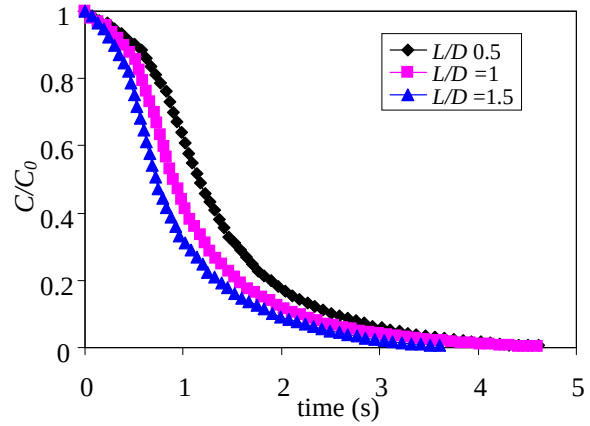

FIG. 9 CONCENTRATION DECAY FOR MEASUREMENT AT POS #2 AND U_m = 15.8m/s

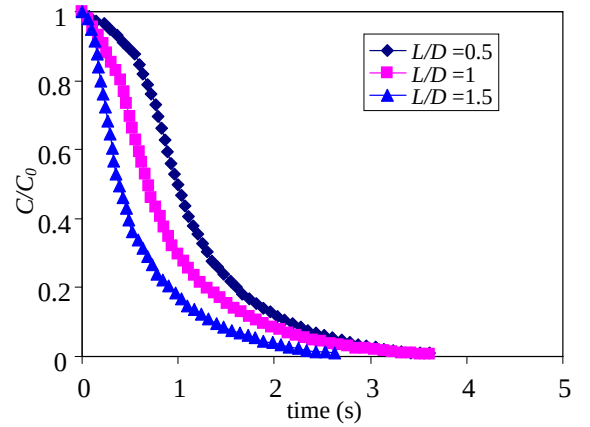

FIG. 10 CONCENTRATION DECAY FOR MEASUREMENT AT POS #2 AND U_m = 20.4 m/s

Air Exchange Rate and Cavity's Ventilation Efficiency

From the concentration decay curve, the air change rate is defined as ratio of the total volume air passing through the zone to and from the outdoors per unit of time to the volume of the zone (ASTM Standard 2009). The air exchange rate, ε (1/s), can be evaluated from the following exponential decay equation:

$$C = C_0 e^{-\varepsilon t} \quad (1)$$

with C_0 being steady-state concentration of tracer gas in the cavity during steady condition, t(s) is time. The linear equation form of Equation (1) is:

$$Ln\left(C/C_0\right) = -\varepsilon t \quad (2)$$

The effective ventilation rate flowing into cavity, Q_v (m³/s) can be calculated by

$$Q_v = \varepsilon V_c \quad (3)$$

with V_c (m3) being the volume of cavity (V_c=LxDxW). Further, the cavity ventilation efficiency, η(%) is defined as ratio between effective ventilation rate against total free stream airflow :

$$\eta(\%) = \left(\frac{Q_v}{Q}\right)\times 100\% = \left(\frac{\varepsilon LDW_C}{U_m D_T W_T}\right)\times 100\% \quad (4)$$

with Q (m3/s) is the free stream flow rate.

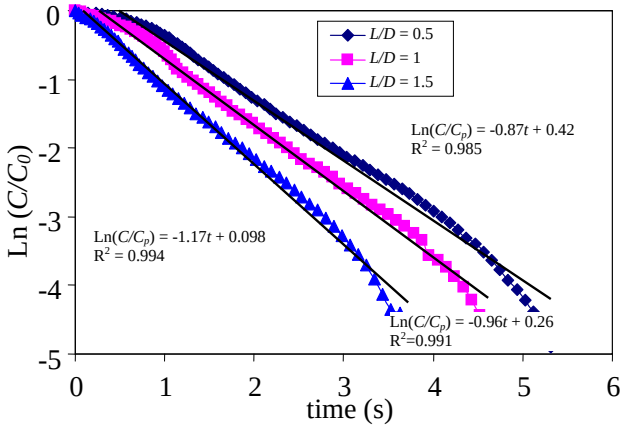

FIG. 11 LINEAR CORRELATION BETWEEN SEMI-LOG VALUES OF NORMALIZED CONCENTRATION, LN(C/C_0), AGAINST TIME (POS #1, U_m=7.07m/s).

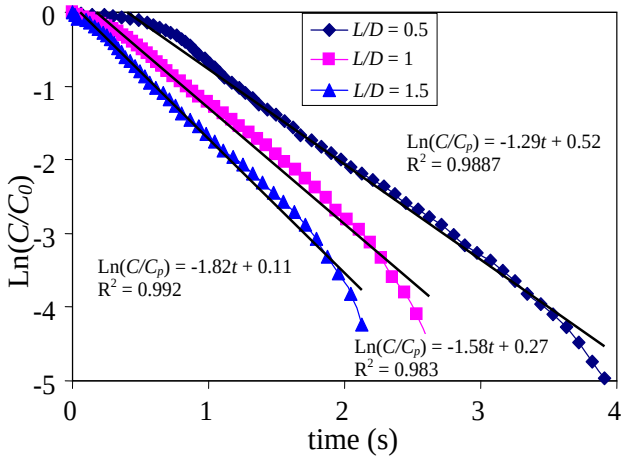

FIG. 12 LINEAR CORRELATION BETWEEN SEMI-LOG VALUES OF NORMALIZED CONCENTRATION, LN(C/C_0), AGAINST TIME (POS #1, U_m = 15.8m/s).

Figures (11) to (13) show the calculated value of air exchange rate measured at #Pos 1 while Figures (14)-(16) for #Pos 2. The summary of air exchange rate for

different aspect ratio and free stream velocities are shown in Figure (17). As expected, the increasing mean flow velocity has resulted in the increasing of air exchange rate for each value of aspect ratio. Similarly, the increasing aspect ratio (reducing of cavity's depth with respect to the cavity's length) also increases the air exchange rate. It is also shown that almost in all results of measurement position #1 is higher than measurement position #2 in the same Reynolds number except for U_m=7.07m/s, L/D=1.5 where measurement position #2 has higher result than position #1. This may be caused by complex swirling vortices around the corner (Shen and Floryan, 1985).

The results of measurement position #1 also show linear correlation with aspect ratio while abrupt increasing can be observed for measurement position #2 between L/D=1 to L/D=1.5. Further, it is presumed that the measured concentrations in position #1 represent average concentration in the cavity and is used to evaluate the cavity's ventilation efficiency.

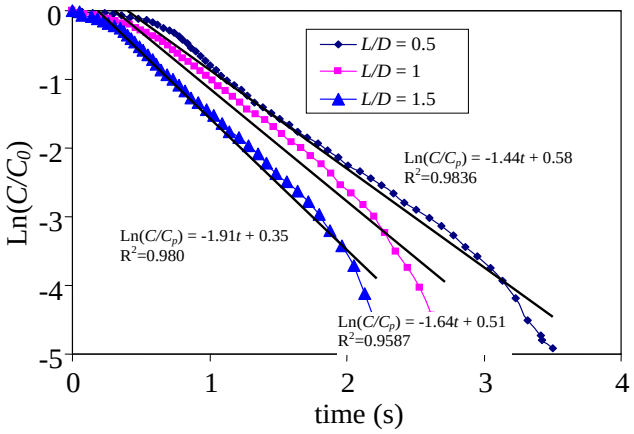

FIG. 13 LINEAR CORRELATION BETWEEN SEMI-LOG VALUES OF NORMALIZED CONCENTRATION, LN(C/C_0), AGAINST TIME (POS #1, U_m = 20.4m/s).

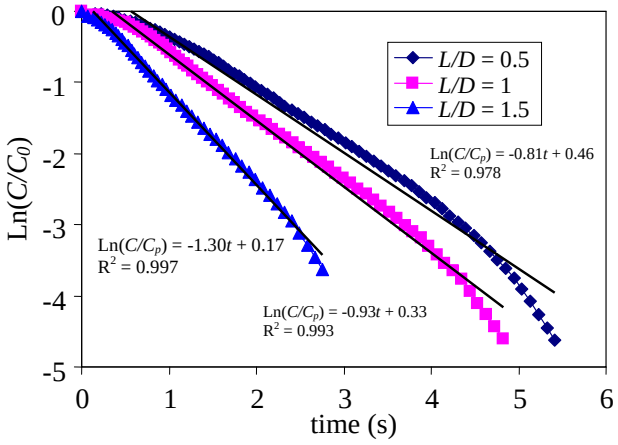

FIG. 14 LINEAR CORRELATION BETWEEN SEMI-LOG VALUES OF NORMALIZED CONCENTRATION, LN(C/C_0), AGAINST TIME (POS #2, U_m = 7.07m/s).

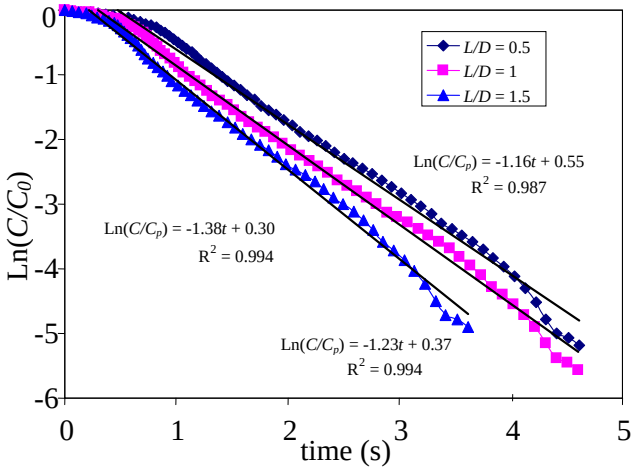

FIG. 15 LINEAR CORRELATION BETWEEN SEMI-LOG VALUES OF NORMALIZED CONCENTRATION, LN(C/C_0), AGAINST TIME (POS #2, U_m = 15.8m/s).

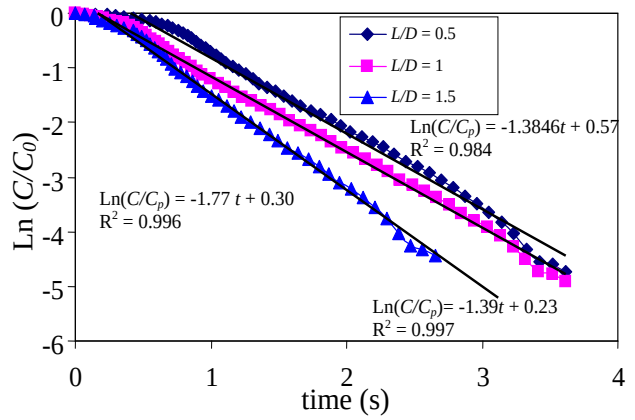

FIG. 16 LINEAR CORRELATION BETWEEN SEMI-LOG VALUES OF NORMALIZED CONCENTRATION, LN(C/C_0), AGAINST TIME (POS #2, U_m = 20.4m/s).

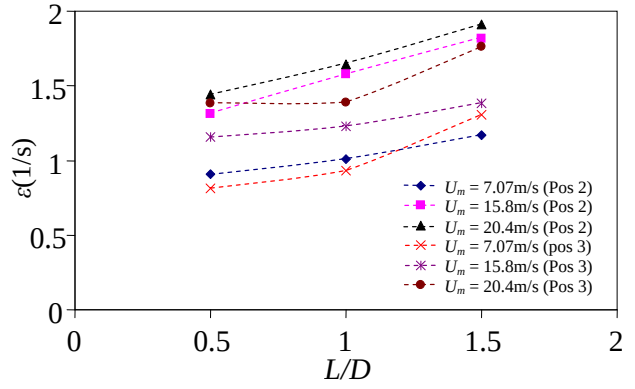

FIG. 17 AIR EXCHANGE RATE AGAINST ASPECT RATIO FOR DIFFERENT FREE STREAM VELOCITY AND MEASUREMENT POSITION

Summarized results of evaluated cavity's ventilation efficiency are presented against L/D ratio and free stream velocity in Figures (18) and (19) respectively. (Arpa 2010) conducted laboratory scale experiment and a side rectangular cavity model similar with by changing cavity's depth to vary the aspect ratio. He also performed measurement in a side cavity of an

underground mine without auxiliary ventilation using SF_6 tracer gas. It was found that the cavity's ventilation efficiency is constant (η=0.01). In the contrary, results of present experiment show that the cavity' ventilation efficiency is function of L/D, Reynolds number, Re_c (i.e. varied with U_m) and also width of cavity as it affects the total volume of cavity. It can be seen also that the increasing of Re_c is inversely proportional to the cavity's effective ventilation. It means that the increasing free stream velocity will increase the air exchange rate on the smaller proportion to the increasing free stream flow rate.

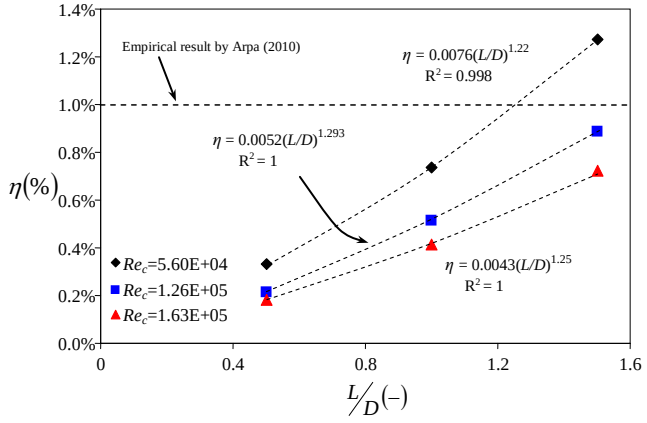

FIG. 18 CAVITY'S VENTILATION EFFICIENCY WITH RESPECT TO L/D RATIO (U_m=7.07m/s, U_m=15.8m/s, U_m=20.4m/s)

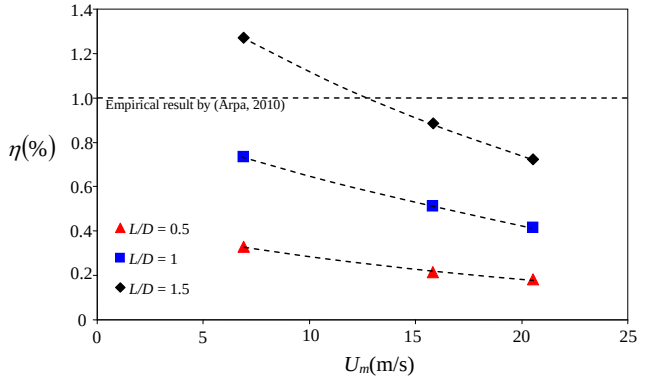

FIG. 19 CAVITY'S VENTILATION EFFICIENCY WITH RESPECT TO FREE STREAM VELOCITY (L/D=0.5, L/D=1, L/D=1.5)

In the real case of underground mine ventilation network, cavities or dead spaces exist in considerable amount and impractical to be quantified. Computational Fluid Dynamic (CFD) is a powerful method to simulate gas dispersion. However, it may only applicable for limited part of ventilation system while for larger scale, larger amount of grid should be considered and the calculation time is enormous. Numerical simulation using random walk method can be developed to covers problem above (Widiatmojo, Sasaki, Arpa, Sugai, Widodo, 2009)

Conclusions

It was verified in general that the value of air exchange rate was proportional to the increasing aspect ratio and cavity's Reynolds number.

The cavity's ventilation efficiency has been investigated for cavity's span-wise ratio, W_c/D=3.3 and free stream cross sectional area D_TxW_T=0.28x0.40. The results have shown proportional relationship of cavity's ventilation efficiency with the aspect ratio. However, it was inversely proportional to the cavity's Reynolds number for the similar aspect ratio.

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